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Market Analysis of the Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept

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This paper presents a detailed market analysis of the U.S. domestic aviation market in support of the NASA subsonic single aft engine (SUSAN) regional aircraft concept. The current scoping of the SUSAN concept is intended to compete in the medium to large (160-180 seats) narrow body market, with range capabilities of up to 2,500 nautical miles, and expected fuel burn reduction up to 40% relative to conventional 2 engine aircraft. Recent historical trends suggest growth in aviation passenger demand will continue to be met by the narrow body fleet of aircraft; however, a comprehensive review is required to understand how these current fleet trends could evolve in the future. Moreover, estimating and forecasting the potential market size is the critical first step when developing a new aircraft concept to determine commercial viability. To assist in the trade space exploration of the SUSAN concept, a generalized traffic and fleet forecast of the U.S. aviation market is conducted. Using publicly available aviation data from the U.S. Bureau of Transportation Statistics and passenger demand forecasts from FAA, a multinomial logit model is estimated to predict the composition of the future fleet by aircraft size. These fleet forecasts are then used as inputs for a fleet evolution model to provide required operational forecasts at the aircraft specific level. Forecast scenarios with and without the SUSAN concept are compared, and a breakeven analysis is performed to evaluate the commercial viability of the SUSAN aircraft from an operating cost perspective. Results from the multinomial logit fleet forecast indicate the narrow body size category of 150+ seats dominating the market, comprising 87% of the future revenue passenger miles market share in 2050 (up from 60% in 2019). Forecast scenarios with the SUSAN concept see a maximum cumulative decline in fuel cost of 20% by 2050, while a breakeven analysis shows competitive advantage of the SUSAN aircraft, due to expected fuel burn reduction, at moderate levels of increased maintenance and capital costs.

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I. Introduction

Over the course of its history, commercial air travel has been defined by its evolutionary growth and technological advancements. One cornerstone in the long arch of aviation engineering has been the ability to reduce the number of engines required for operations while simultaneously improving fuel efficiency on a per seat mile basis. The growing need to reduce aviation's environmental impact through greenhouse gas emission is considered in the International Civil Aviation Organization (ICAO) aspirational goals for aviation fuel efficiency [1].The subsonic single aft engine (SUSAN) concept continues the legacy of technological advancement in engine design and efficiency while also addressing global needs to reduce emissions set by ICAO standards.

The purpose of this paper is to continue the trade space exploration and market analysis of the SUSAN narrow body aircraft concept first discussed in Jansen et al. [2]. The concept aircraft design characteristics are intended to compete within the large single aisle market, with a seat count of 180, range capability of up to 2,500 nautical miles (NM), cruise Mach number of 0.785 and introduction year of 2040. The advanced single engine design coupled with sustainable alternative fuels (SAFs) have the potential to drive down fuel costs and emissions by 50% per seat mile while still competing in nearly all the same markets as conventional 2 engine narrow body aircraft. This paper expands on the previous market assessment by conducting a comprehensive future fleet analysis of the United States domestic commercial aviation market, with the objective of simulating the evolution of the future fleet to better understand the impacts of introduction the SUSAN concept aircraft. We first generate a detailed traffic demand and fleet forecast, which are used as inputs for a fleet evolution model to define the future composition of aircraft in the U.S. domestic market. A baseline fleet evolution forecast is compared against an alternative fleet forecast that includes the SUSAN concept aircraft. The market shares from the fleet evolution analysis are further used to inform a breakeven analysis of the operating and capital costs between the two scenarios.

The paper is structured as follows: Section II defines the traffic and fleet forecast methodology and outputs from the fleet evolution analysis; Section III presents the framework for the cost modeling and breakeven analysis results; and Section IV provides a conclusion of the market analysis.

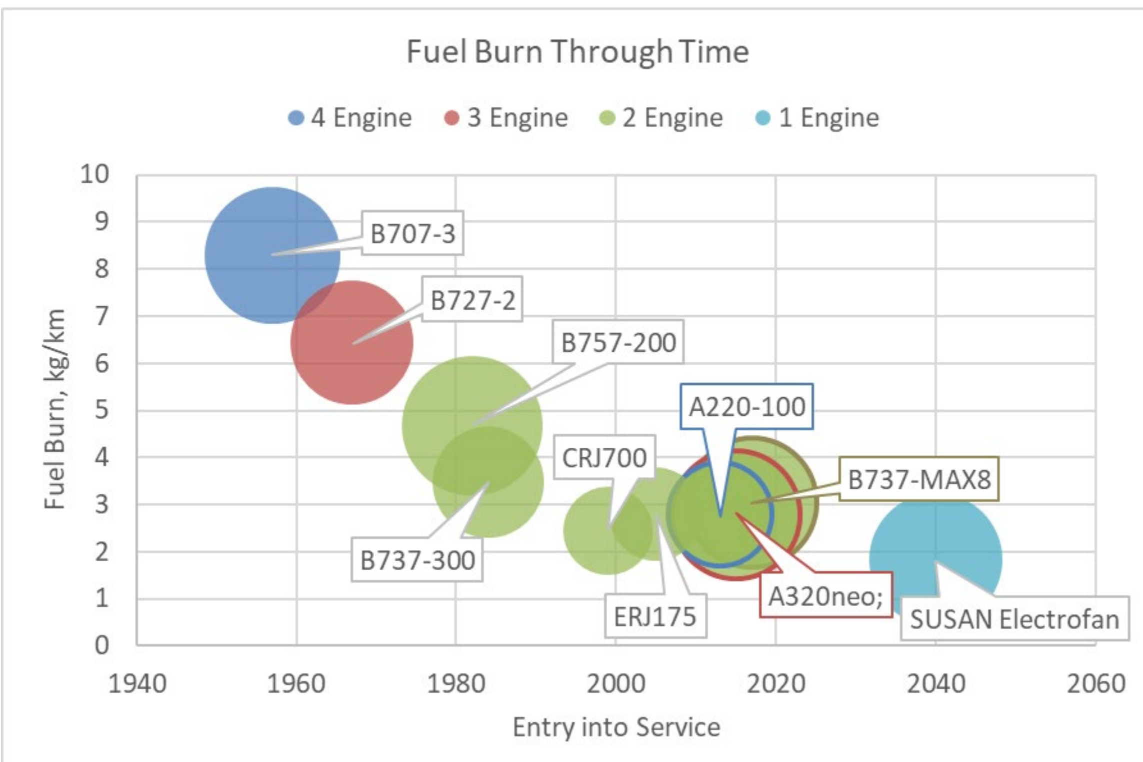

Fig. 1 Evolution of Aircraft Engine Configurations

II. Traffic and Fleet Forecast

A. Historical Trends in U.S. Domestic Aviation

The U.S. domestic market for air transportation has experienced significant evolution and growth over the past four decades since de-regulation of the passenger market occurred in the early 1980s. Passenger demand, measured in revenue passenger miles, have increased nearly 300 percent during the period 1980 to 2019 [3], while the in-service fleet grew from 2,529 to approximately 6,000 aircraft during the same period. However, aviation's contribution to U.S. GHG emissions has remained relatively flat at 2.7 percent [4] even as RPMs and enplanements have grown, thanks in part to continued increases in aircraft and engine fuel efficiency. These gains in efficiency from conventional means such as engine re-designs and tweaks to the tube-and-wing airframe will eventually reach a point of diminishing marginal returns, and emissions are forecasted to increase substantially over the next 30-years without major technology advancements [5]. The need for a more sustainable and cost-efficient aircraft has led to the design of the SUSAN aircraft and follows in aviation's history footsteps of moving incrementally from 4 down to 2 engines over the past 70 years (Figure 1). The reduction in the number of engines has historically driven the significant improvement in fuel efficiency and is expected to continue when moving to a single engine.

Over the course of the past 30 years, narrow body aircraft have made up the vast majority of passenger enplanements and revenue passenger miles (RPMs) in the domestic market. Recent trends in the domestic US aviation market have also seen robust growth in the overall capacity and range capabilities in narrow body aircraft. A comparison of seat capacity (weighted by operations) between 1990 and 2019 (Figure 2) shows a significant shift in the distribution to larger aircraft, with the average number of seats increasing from 138 to 162 over this period. A similar change occurred in the distribution for distance flown in miles (weighted by operations, Figure 3) where the average distance flown for narrow body aircraft increased from 532 to 867 miles.

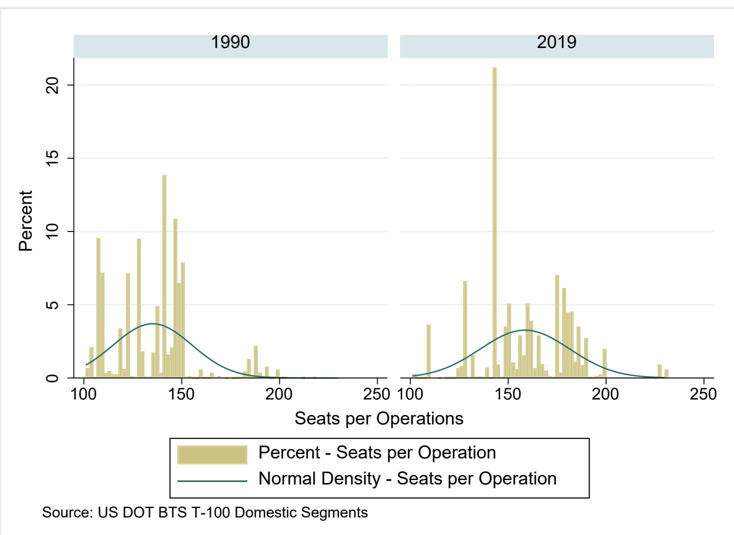

Fig. 2 Distribution of Average Narrow Body Capacity in 1990 and 2019

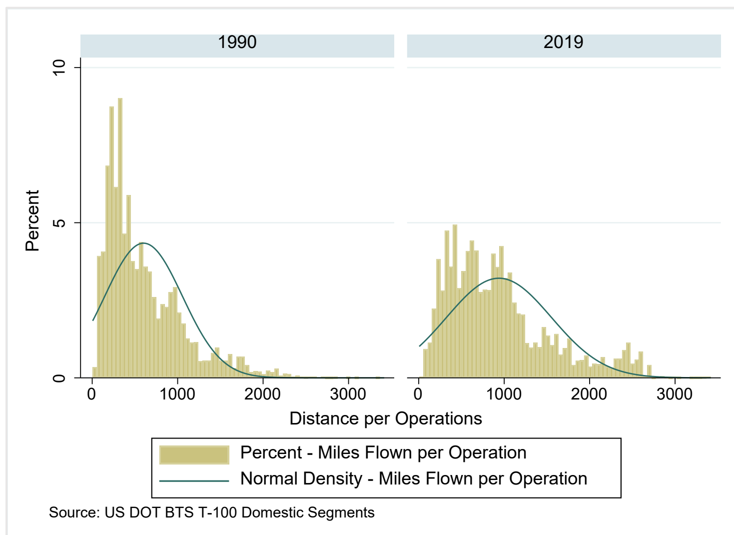

Fig. 3 Distribution of Average Narrow Body Miles Flown in 1990 and 2019

The increase in range and passenger capacity in the narrow body market has coincided with improved operating efficiencies, extending the dominance of the narrow body market share relative to other aircraft categories. Figure 4 presents the distribution of US domestic RPMs by aircraft categories from 1990 to 2019. Data is sourced from the

U.S. Department of Transportation Bureau of Transportation Statistics, Form 41 Traffic Schedule T-100.[4] Aircraft categories are defined by regional aircraft with up to 100 seats, wide body (twin aisle) aircraft and four separate narrow body categories divided into 25 seat increments.[5] The narrow body market was subdivided in order to provide a richer examination of the trends and changes for this market over the time series. The general trends confirm the growth in the narrow body market (as measured by RPMs), with significant upgauging occurring within the narrow body market itself. Noticeably, the smallest narrow body market (100-125 seats) lost the largest share of total RPMs, are operations shifted away to either smaller regional jets or larger (126+ seat) narrow bodies. The increase in regional jet RPMs during the period after 2003 was due to a combination of airline industry-wide reorganization post-9/11 through bankruptcies and mergers, in addition to regulatory changes to the Scope clause affecting regional jet capacity and crew salaries [6], and RPM growth has since plateaued in this market. The domestic wide body market has also lost considerable market share since the early 1990s as narrow body aircraft increased competition on longer segments as range and economic performance continued to improve. Overall, since 2003 the two largest narrow body categories increased their combined RPM market share from 27% to 61% by 2019, while all but the regional jet market (7.5% in 2003 to 11% in 2019) have seen a decline in their market share.

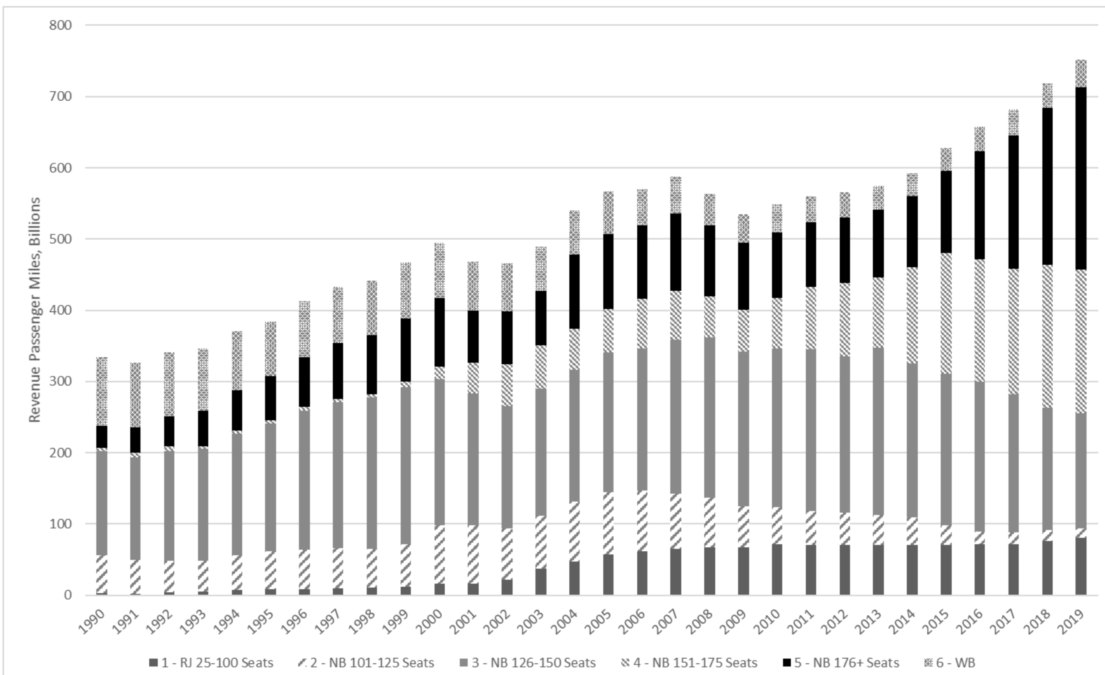

Fig. 4 U.S. Domestic Revenue Passenger Miles by Aircraft Size Category 1990-2019

[4] The BTS T-100 dataset contains monthly domestic non-stop segment information (filtered for U.S. carriers only for this analysis), and includes data such as carrier, origin & destination airports, aircraft type, enplanements, available capacity, and aircraft flight hours.

[5] The piston and turbo prop aircraft market was excluded from the figure given its relatively marginal share (1% or less) of total RPMs over this period.

B. Long-Run U.S. Domestic Traffic Demand Forecast

While the current market trends suggest the narrow body market, specifically large narrow bodies with capacity 150 and greater, will continue to grow in the near term, it is important to consider first how the overall demand for commercial passenger travel could evolve into the future. The Federal Aviation Administration (FAA) publishes official annual domestic forecasts of U.S. airports under the Terminal Area Forecast (TAF) program. This model was enhanced in 2015 (TAF-Modernization or TAF-M, [7]) to include origin-destination (OD) pair modeling of passenger demand and produces forecasts of enplanements and commercial operations for airports with over 100,000 total annual enplanements (99% of all commercial traffic domestically). The most recent publication of the TAF-M's long-term forecasts was released in 2021 and estimated out to 2050. The TAF-M forecasts at the OD pair level by airframe type, and Figure 5 presents the aggregated U.S. passenger and RPM forecasts. The forecast covers the COVID-19 pandemic downturn in aviation travel in 2020 and subsequent recovery by 2025 in terms of both passengers RPMs. Forecasted aviation traffic over the period 2019 to 2050 is estimated to grow at an annual rate of 1.8%, compared to the 1.6% compound annual growth (CAGR) over the historical period 2000 to 2019. In general, FAA's forecast of the U.S. domestic market compares reasonably with other industry and governmental sources, with Airbus, Boeing, ICAO and EIA predicting 20-year RPM CAGRs to be between 1.7% and 2.6%.

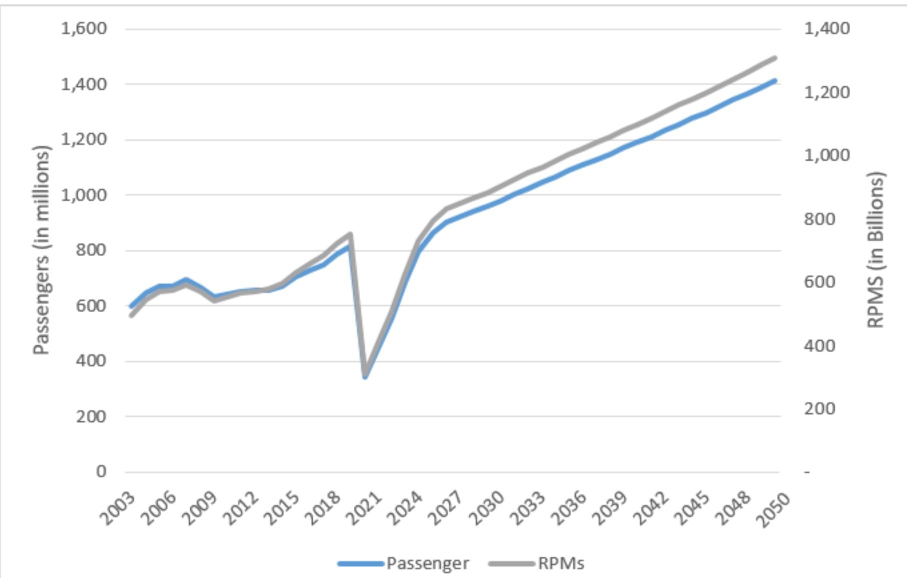

Fig. 5 FAA's Terminal Area Forecast of Domestic Passengers and RPM

C. Generic Fleet Forecast

The advantage of the TAF-M is the disaggregated nature of the traffic forecast, produced at the OD pair segment level, which allows for detailed analysis of network and passenger flow demand. However, one major drawback exists when attempting to understand how the fleet changes over the course of the forecast, since the TAF-M assumes a static fleet stock over the forecast period. In other words, the traffic forecast assumes the same aircraft type operating in 2019 will still be in service at the end of the forecast in 2050 (e.g., a B757-200 operating on an OD pair in 2019 will remain in the forecast through 2050). This simplification limits the ability to use the TAF-M for any direct analysis of the future fleet, as it fails to take into account basic market dynamics, such as the evolution of aircraft capacity (upgauging), or the growth and replacement of the future fleet.

A key requirement for the SUSAN concept market analysis is to evaluate the market demand for narrow body aircraft in the future. This type of aircraft category forecast can be modeled through a multinomial logit (MNL) regression analysis, where the dependent variable contains multiple categories that are considered mutually exclusive from each other. For this analysis, the aircraft size defined by seat ranges and type is the categorical (dependent) variable of interest (Table 1). These type of discrete choice models has been utilized extensively in previous transportation research [8, 9] and specifically in the case of predicting aircraft type and size in the U.S. domestic market [10]. The modeling effort undertaken here extends this framework to predict and forecast the future fleet size using historical BTS T-100 data in combination with the TAF-M as the exogenous forecast traffic demand input.

The theoretical underpinning for this type of discrete choice modeling is the choice set of possible aircraft an airline can select and assign to a particular flight segment. Airlines maximize profits and minimize cost with respect to their choice of aircraft, and the expected probability of choice j of k aircraft categories can be expressed by the following probability distribution function:

$$P(y_{i=j}) = \exp(X_i\beta_j) \,/\, \sum_{k=0}^{j} \exp\,(X_i\,\beta_k) \quad (1)$$

Where the expected outcome (probability) for category j is a function of independent variables in vector X_i and estimated vector of coefficients β. The independent variables for this analysis included: RPMs by aircraft category and segment, segment length indicators[6], airport hub status indicator at origin and destination (top 30 U.S. airports), market size (number of available aircraft size categories) and a linear time trend.[7] The model parameters are estimated using historical annual BTS T-100 data from 2003-2019 at the bidirectional U.S. domestic OD pair and aircraft category level, totaling over 318 thousand observations in the final dataset. The MNL model used seat class category 1 aircraft (piston and turbo props) as the reference case, with results presented in appendix of the paper for brevity, though at a high level the results are efficiently estimated and statistically significant at the 1% significance level. The relative odds ratios (alternatively referred to as relative risk ratios) are consistent with expectations of higher likelihoods for larger aircraft categories being selected given an increase in RPM demand, longer distance flights, or if the airport is a top 30 hub. Additionally, the time trend variable indicates movement towards larger narrow body aircraft over the historical period.

Table 1 Seat Class Category Definitions used for Multinomial Logit

Seat Class Category	Seat Class Definition	Example Aircraft Types
1	Piston/Turbo Prop ≤ 100 Seats	ATR42/7, CNA280, Q400
2	Regional Jets 25-100 Seats	CRJ200/700, ERJ145/175
3	Narrow Bodies 101-125 Seats	A220-100, ERJ195
4	Narrow Bodies 126-150 Seats	A220-200, A319, B737-7
5	Narrow Bodies 151-175 Seats	A320, B373-8
6	Narrow Bodies 176+ Seats	A321, B737-9
7	Wide Bodies	A330, B787

As a means to measure the performance of the MNL model, the aircraft categories were predicted for each observation and compared against the actual aircraft category observed. The MNL will produce probability values for each aircraft category relative to the alternatives and the combined probabilities will sum to one by definition. These probabilities were applied to the total passenger count by OD pair and aircraft category to estimate a predicted passenger share distribution. Table 2 present the comparison of the predicted passenger share against the actual observed share by aircraft category in 2019, which shows very close alignment across categories with the margin of error never exceeding 3%. Additional checks were performed for other historical years and across different distance ranges, with similar close alignment.

Table 2 Comparison of MNL Model Prediction and Actual Passenger Share by Aircraft Category

Aircraft Seat Class Category	Actual 2019 Passenger Share	Predicted 2019 Passenger Share
Piston/Turbo Prop ≤ 100 Seats	1%	2%
Regional Jets 25-100 Seats	19%	17%
Narrow Bodies 101-125 Seats	2%	4%
Narrow Bodies 126-150 Seats	27%	27%

[6] Segment lengths were classified into 5 categories based on distance: <250 miles, 250-500 miles, 501-1200 miles, 1201-2000 miles, and 2001+ miles.

[7] Additional variables were considered, but were ultimately not included in the final MNL model specification. These included additional airport/route information such as runway counts, distance to nearby airports and gate constraints, additional macroeconomic data on population and income, and a collapsed set of aircraft categories for the dependent variable. Given the primary purpose of this model as a forecast tool for aircraft size categories, a more parsimonious specification was preferred to reduce forecast input error. Therefore, collinearity issues with the additional airport and route data ruled out their inclusion, while the macroeconomic infomation were already indirectly captured in traffic demand forecast from the TAF-M. Finally, a reduced set of aircraft choice by collapsing categories did not yield improved model or forecasting performance.

Narrow Bodies 151-175 Seats	22%	23%
Narrow Bodies 176+ Seats	26%	23%
Wide Bodies	2%	4%

Given the accuracy of the MNL in-sample predictions, the next step was to incorporate the TAF-M passenger demand forecast to produce fleet-wide category predictions by forecast year. Since the underlying historical BTS T-100 and TAF-M data were nearly perfectly aligned (correlations between the two datasets were 0.99 once freighter and international trips were dropped from TAF-M), the use of the TAF-M forecast was straightforward and did not require any external inputs. The TAF-M OD pair RPM forecast values were used as inputs to predict the future distribution of aircraft categories, measured by total passengers, with results from the forecasting process presented in Figure 5.[8] These results show significant growth in the two largest narrow body categories in the outer years, accounting for 86% of total passengers by 2050, up from 49% in 2019. The model predicts that while all other categories will experience declining passenger growth, the two largest narrow body categories are predicted to grow at an annualized rate of 3.6% over the 32-year period.

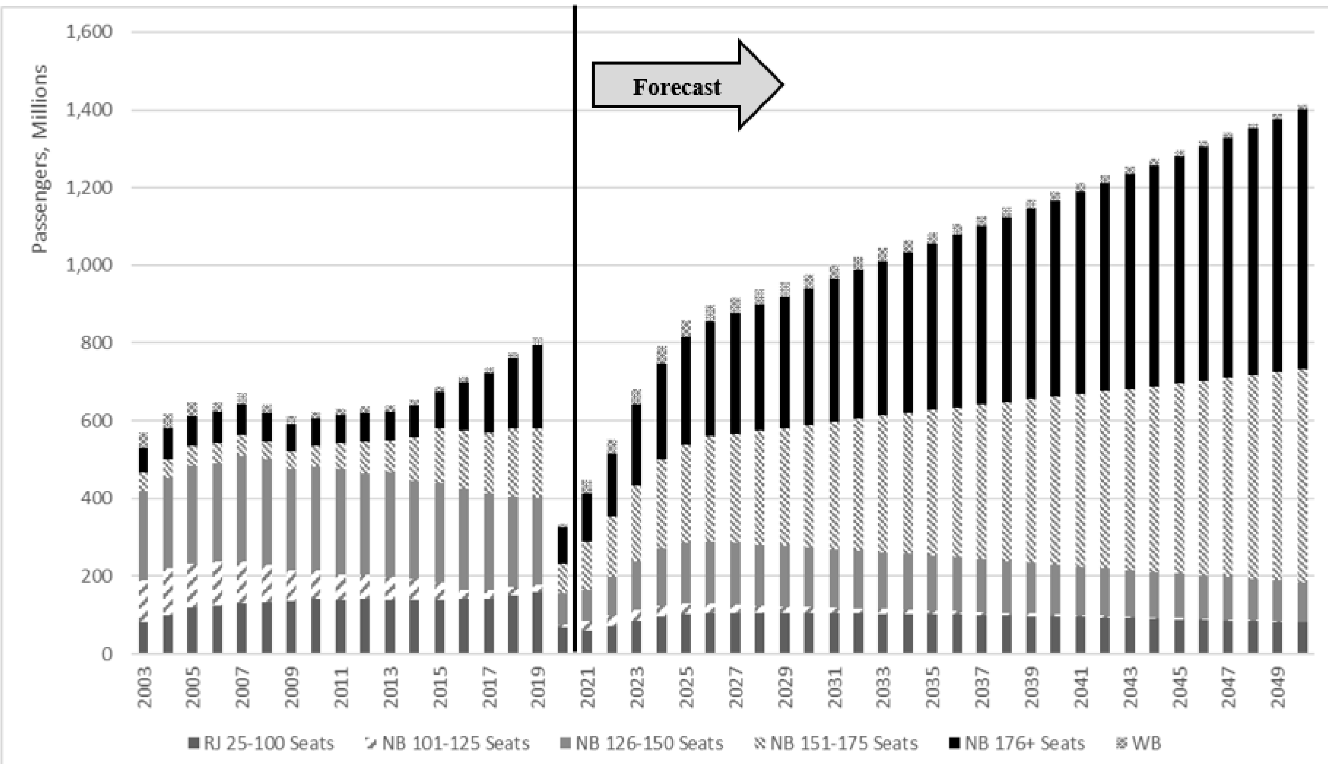

Fig. 5 Fleet Size Category Forecast Output to 2050 from the Multinomial Logit Model

[8] In addition to the forecasted RPM values from the TAF-M, the other (possibly) time variant explanatory variables (i.e., variables unrelated to distance) were included in the forecasting process. There variables include the following assumptions: the list of top 30 origin and destination airports remained unchanged and the maximum number of aircraft categories available historically by OD pair was used in the forecast period, while the linear time trend increased monotonically up through 2050.

D. Fleet Evolution

The final forecasting step in the SUSAN market analysis is to evaluate the combined traffic and generic fleet forecast output from the MNL modeling given a set of specific growth and replacement (G&R) aircraft. This type of analysis, known as fleet evolution, takes into account the retirement process of both the base year and future fleet and the needed capacity required to meet future levels of traffic demand. This analysis used proprietary software developed by FAA to assist in the fleet evolution process.[9] The fleet evolution estimation requires several steps and Figure 6 presents a schematic overview of the methodology used for the market analysis. To begin, a set of data inputs are needed to define the base year origin-destination network (assumed to be static during the forecast), the base year fleet of aircraft, aircraft retirement curves, a defined list of available G&R aircraft, and demand forecast targets.[10] These data inputs then inform the estimation of the number of aircraft retirements, retained aircraft in the fleet and number of G&R delivers required to meet future demand. Allocation of the G&R capacity is determined by a market share model defined by the user (e.g., aircraft A receives 50%, while aircraft B and C receive 25% each). The tool then deploys the newly delivered fleet of aircraft onto the network of OD pairs, and calculates as output the associated operational statistics (including total fuel burn).

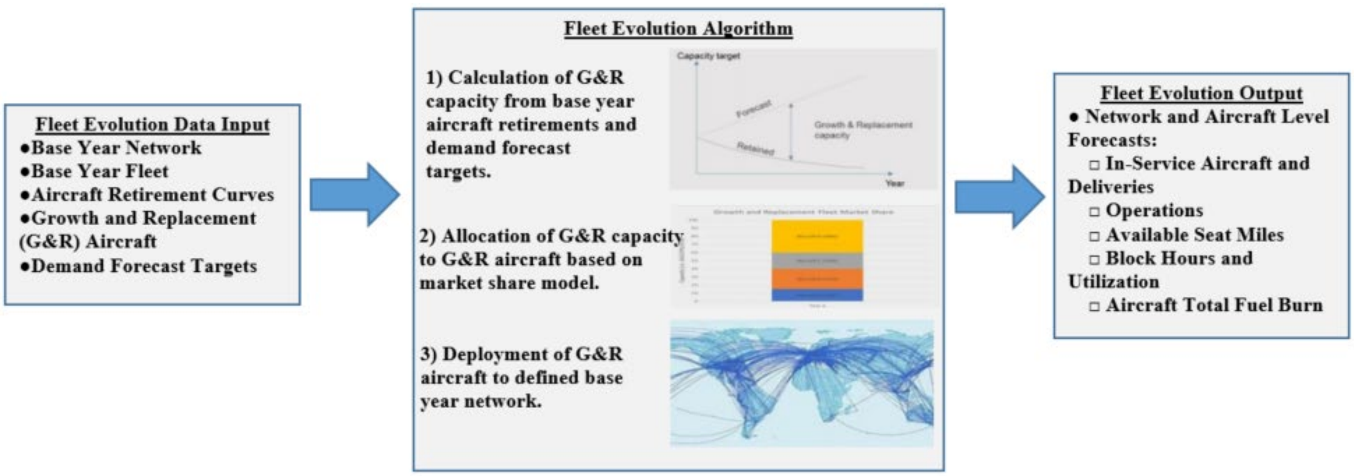

Fig. 6 Fleet Evolution Schematic

Forecast demand targets for the fleet evolution process were constructed based on the traffic and generic fleet forecasts. The primary forecast target is available seat miles (ASMs), which measures the total available volume of demand, estimated as RPMs divided by a seat class specific load factor.[11] A secondary forecast target for the in-service fleet is calculated by the following identity:

$$In - service\ fleet = {ASMs}/{Utilization * Capcity * Speed} \tag{2}$$

Where utilization is measured in annual block hours per aircraft, capacity is measured as average seats per category, and average speed is MPH. Fleet assumptions for utilization, capacity, and speed are based on historical BTS T-100 and Form 41 P5.2 data and are provided in a summary table in the appendix. For both the ASM and in-service fleet targets, the dimensions required for the fleet evolution tool are by aircraft seat class and distance band range (measured in 500 nm increments) by the following forecast target years: 2020, 2024, 2030, 2040 and 2050.

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[9] FAA's FLeet Evolution, Estimation and evaluaTion Builder (FLEET-Builder), part of FAA's Aviation Environmental Tool Suite: https://www.faa.gov/sites/faa.gov/files/2022-03/508.20220323_1530_Grandi_Analysis_and_Tools_Development_v02.pdf

[10] The base year network and fleet are sourced from a proprietary US DOT common operations database of commercial operations for the year 2018. These data are tightly aligned with the BTS T-100 data and provide important information on the base year fleet, such as the fleet size by specific aircraft types (e.g., B737-700), and the distribution of age, seats, and payload by aircraft type.

[11] Load factors by aircraft seat class were estimated as a 5-year moving average beginning in 2015 (excluding impacts from the COVID-19).

In order to evaluate the potential impact of the introduction of the SUSAN concept aircraft into the future fleet, a baseline fleet mix and the associated operations and fuel burn is first estimated. Table 3 delineates the available G&R fleet of aircraft for the two narrow body seat class of interest and corresponding aircraft characteristics including average capacity, maximum range, market introduction date, and approximated purchase price (assumed to be 50% of list price). Under the baseline forecast, only the non-SUSAN aircraft are available for growth and replacement purposes. In the alternative scenario, the SUSAN aircraft are assumed to compete in seat class category 6 and 7, with introduction dates of 2040. The estimated purchase price is presented as 40% above the reference B737-MAX8 and -9 aircraft; however, this value is parametrically adjusted to allow for a range of values in the cost modeling analysis.

Table 3 Growth and Replacement Aircraft for Narrow Body Seat Classes 6 and 7

Airframe	Seat Class	Seat Class ID	Seats	Max Range (NM)	Market Intro	AC Price (2018 $)
A320-NEO	NB 151-175 Seats	6	175	3,500	2016	55,300,000
B737-MAX8	NB 151-175 Seats	6	175	3,515	2018	59,731,500
SUSAN SC-6	NB 151-175 Seats	6	160	2,500	2040	83,624,100
A321LR-NEO	NB 176+ seats	7	200	4,000	2018	64,750,000
A321-NEO	NB 176+ seats	7	198	3,500	2017	64,750,000
A321XLR-NEO	NB 176+ seats	7	200	3,500	2022	64,750,000
B737-MAX9	NB 176+ seats	7	189	3,515	2017	63,317,500
B737-MAX10	NB 176+ seats	7	210	3,215	2020	66,265,000
SUSAN SC-7	NB 176+ seats	7	180	2,500	2040	88,644,500

Fleet evolution modeling requires assumptions on market share allocation for new aircraft, and this analysis used two market share scenarios to help bound the SUSAN aircraft introduction and diffusion into the fleet. In both scenarios, SUSAN is assumed to enter the market in 2040. The two scenarios were as follows:

- Technology Transition (TT): SUSAN enters the market with an increasing share to simulate gradual increase in OEM production rates.
    - Year 2040: 5% market share
    - Years 2041-2045: 10% in 2041 increasing by 10% increments up to 50% by 2045
    - Year 2046: 75% market share
    - Years 2047-2050: 100% market share
- All Market Share (ALL): SUSAN enters the market with 100% market share in 2040. This is the most rapid possible introduction rate to establish an outer-edge of the analysis space.

The two scenarios predictably produce unique results in terms of total block hours, total deliveries, and total costs across the fleet. As previously noted, the SUSAN aircraft is assumed to enter the market in seat classes 6 and 7 with an assumed average capacity that is towards the lower bound of the seat class, which means that more SUSAN aircraft are required to meet the same passenger demand relative to competitor aircraft. This leads to higher block hours and deliveries in both scenarios relative to the baseline, which effectively also increases costs. The results for both scenarios are presented in the Cost Model Analysis section, but the scenarios do not influence the later breakeven analysis as that analysis is done per-aircraft and not fleet-wide.

III. Future Market Cost Analysis

The cost analysis is comprised of two separate analyses—the first is a full cost model that looks across the entire fleet of aircraft to assess the overall change in aircraft costs, while the second is a breakeven analysis that seeks to identify the points at which SUSAN costs are equivalent overall to competitor costs.

A. Cost Model Analysis

The cost model combines the outputs of the fleet forecasting with assumptions on operating and capital costs to generate estimates of total costs across the entire growth and replacement fleet. The cost model is estimated with a base year of 2018, and extends out through 2050, although the main focus of analysis is the 11-year period from 2040 to 2050, as 2040 is when SUSAN aircraft are assumed to enter the market.

The cost model calculates costs both for a "baseline scenario", which assumes that no SUSAN enter the market and therefore solely includes competitor aircraft, and a "SUSAN scenario", which includes both competitor aircraft and SUSAN aircraft. The baseline scenario is fixed with one set of results, but there are multiple results for the SUSAN scenario, based on changing assumptions of the rate of entry into market, the assumed fuel burn reduction, and the purchase price premium.

1. Data Assumptions

Data are compiled for capital costs, fuel costs, crew costs, and maintenance costs across seat classes 3 through 8. SUSAN is assumed to enter the market with two variations, one in seat class 6 and one in seat class 7. The main assumptions used in the analysis are described in Table 4. The assumptions for the SUSAN aircraft are the same as competitors for the finance rate, depreciation rate, crew cost per block hour, and maintenance cost per block hour. The key assumption differences are in the purchase price and the fuel burn rates, both of which vary in the model across different scenarios. The full cost model tested three different fuel burn reduction scenarios (30% fuel burn, 40% fuel reduction, and 50% fuel reduction) and five different purchase price premium scenarios (10% price premium, 20% price premium, 30% price premium, 40% price premium, and 50% price premium). The differences in SUSAN are calculated relative to B737-9MAX for the SUSAN in seat class 7 and relative to the B737-8MAX for the SUSAN in seat class 6.

Table 4 Cost Model Assumptions

Data Type	Data Source/Value
Total Deliveries	Fleet forecasting, specific to each aircraft type
Total Block Hours	Fleet forecasting, specific to each aircraft type
Fuel Burn (kg)	Fleet forecasting, specific to each aircraft type
Cost of Fuel	$2.16/gallon
Maintenance Cost per BHR	Sourced from FAA BCA guidance — varies by seat class [11]
Crew Cost per BHR	Sourced from FAA BCA guidance — varies by seat class [11]
Purchase Price	One-half of list price, specific to each aircraft type [12 – 18]
Finance Rate	7.2% (sourced from IATA's weighted average cost of capital) [19]
Depreciation Rate	3.4% (sourced from airline annual reports) [20 – 24]

To ensure the general validity of the model, the cost model results for the base year, 2018, were compared with publicly available sources on operations and costs. The validation showed that generally the cost model results were within a reasonable margin of error (5%) relative to the public sources. It is worth noting that the analysis of the cost model is generally concerned with the relative difference between the costs in the baseline and the SUSAN scenarios, rather than the total size of the costs, meaning that any errors in estimation of costs are likely to be present in both the baseline and SUSAN scenarios, and that such errors will get canceled out when calculating the difference in costs.

2. Results

The cost model estimated costs across the baseline scenario, and then compared the baseline costs to the costs of multiple scenarios with SUSAN aircraft introduced in 2040. Overall, the model predictably shows a significant reduction in fuel costs across the entire fleet, although larger price premiums result in an overall increase in costs across the 11-year analysis period from 2040 to 2050.

Figure 7 shows the change in fuel costs across all aircraft from 2040 to 2050 for the three fuel reduction scenarios and the two SUSAN fleet introduction scenarios. The graph shows that all scenarios experience reasonable fuel

savings, with the total reduction in 2050 ranging anywhere from a 6 to 20 percent decrease. These findings suggest the potential for sizable fuel savings across the entire industry, even with continued use of non-SUSAN aircraft.

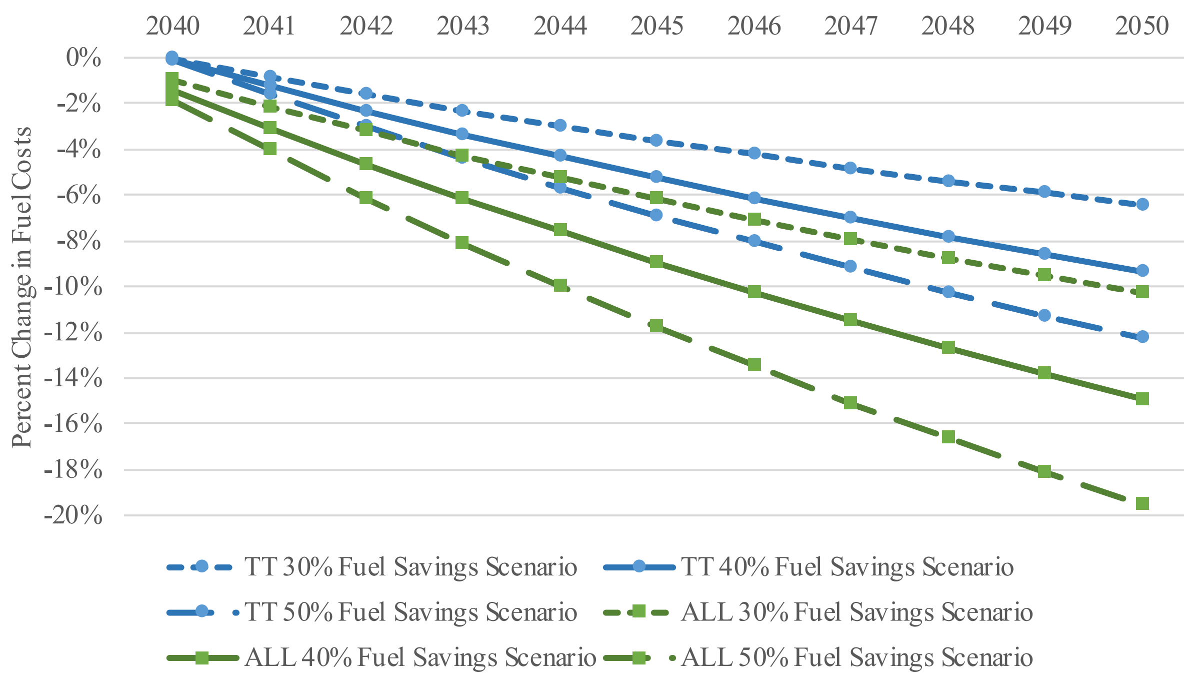

Fig. 7 Change in Fuel Costs Across All G&R Aircraft

The following graphs show the change in capital costs across all aircraft from 2040 to 2050 for the five price premium scenarios, where Figure 8 shows the results for the Technology Transition Scenario and Figure 9 shows the results for the All SUSAN Scenario. The graph shows that the size of the overall capital cost increase varies significantly by scenario, and that the pattern of the increase over time is different across the two fleet introduction scenarios. Results are presented for all five price premium scenarios.

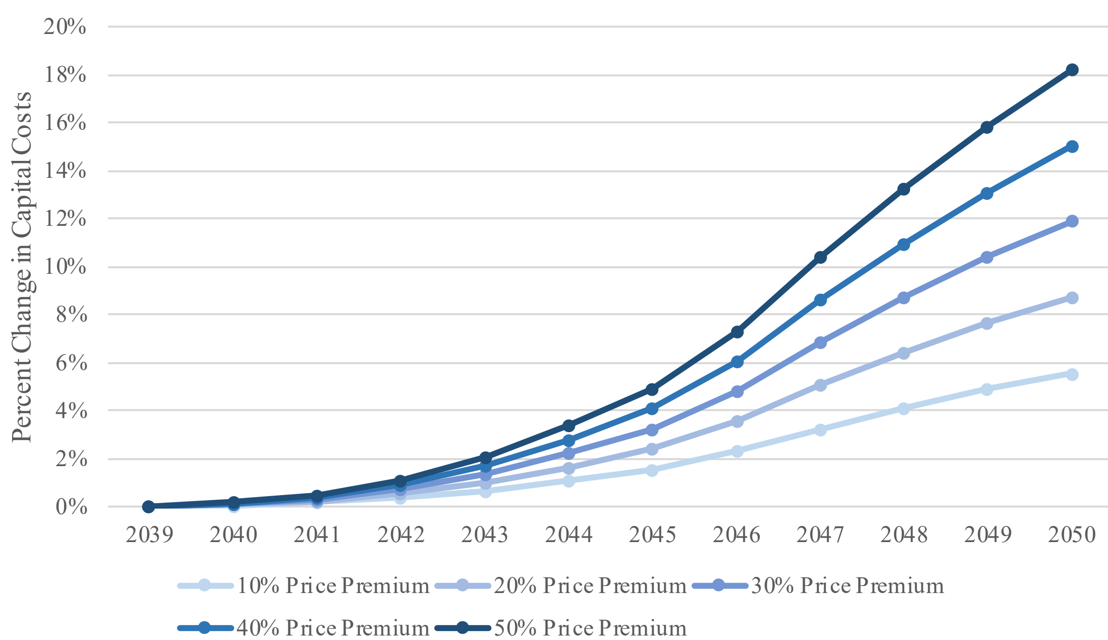

Fig. 8 Change in Capital Costs Across All G&R Aircraft – Technology Transition Scenario

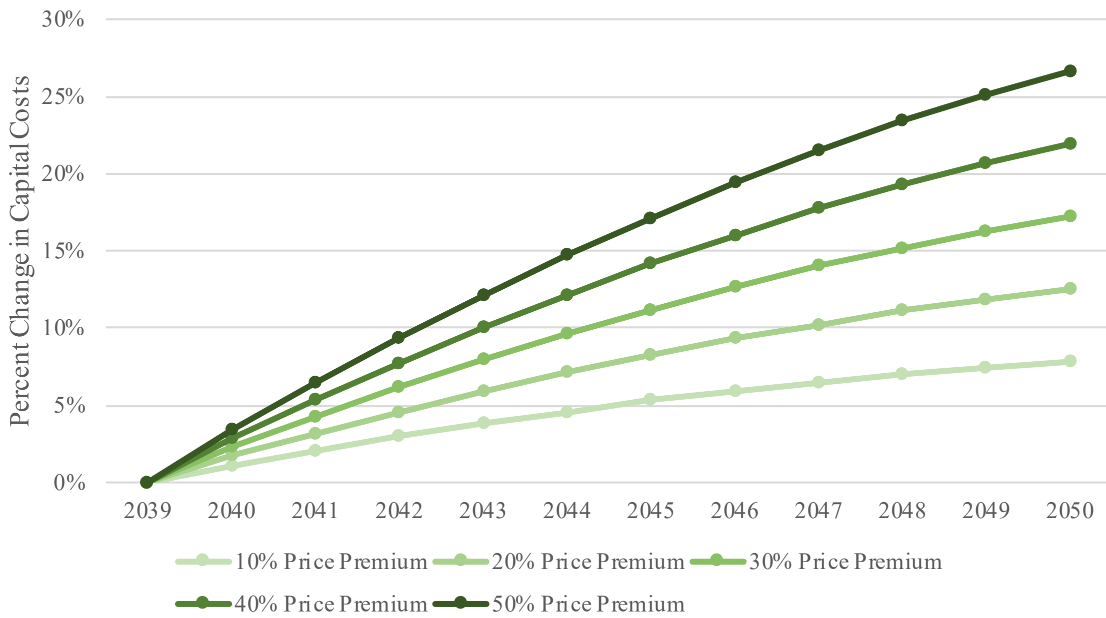

Fig. 9 Change in Fuel Costs Across All G&R Aircraft – All SUSAN Scenario

The analysis then considered the impact of SUSAN on total costs across the G&R fleet. The total costs included all costs estimated in the model, meaning that the change includes fuel costs, maintenance costs, crew costs, and capital costs. As previously noted, the crew and maintenance cost per block hour is held constant for SUSAN relative to its competitors in the same seat class. The results for the change in total costs are presented for both fleet forecasting scenarios, with a fixed assumption of a 40% reduction in fuel burn and a 20% increase in the purchase price. Results can be seen in Figure 10 —for the full results for all fuel burn and price premium scenarios, refer to the Appendix.

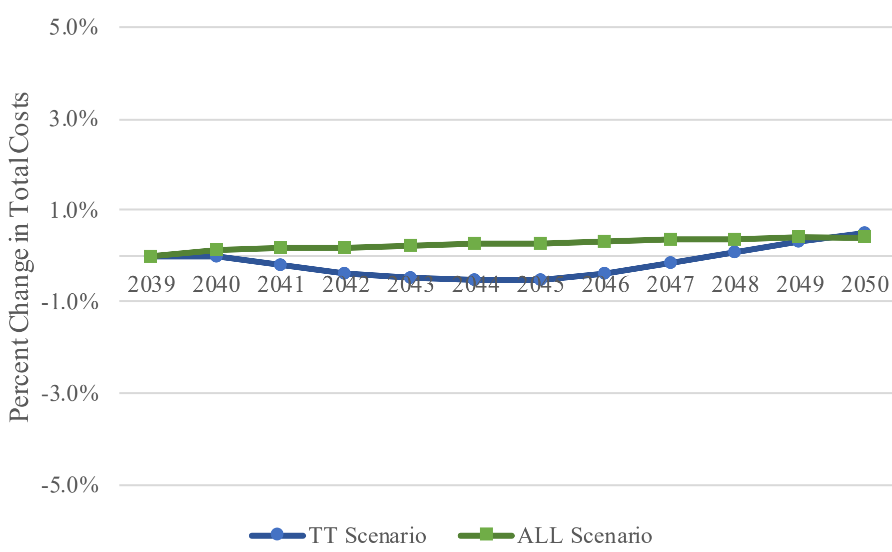

Fig. 10 Change in Total Costs Across All G&R Aircraft – 40% Fuel Reduction, 20% Price Premium Scenario

The conclusions do differ based on the assumed fuel reduction and price premium, however generally, the change in total costs follows a similar pattern for most assumptions. The Technology Transition Scenario results in

initial cost savings, before the overall costs end up increasing toward the end of the analysis period, whereas the All SUSAN Scenario only ever has increases in total costs. This is likely because the higher upfront capital costs and the continued purchases of SUSAN aircraft for every analysis year outweigh the fuel cost savings. It should also be stated that the relative cost increases under both scenarios are marginal and under 1% of total costs. To understand the long-run impacts of SUSAN, an analysis period longer than 11 years would need to be assessed. In the long run, it is likely the case that SUSAN will produce an overall cost-effective scenario, but it may take time to realize those savings market-wide given the lag in fleet diffusion and retirement of older non-SUSAN aircraft.

C. Breakeven Analysis

A breakeven analysis was conducted to understand the point at which lifecycle costs for SUSAN aircraft are roughly equivalent to the lifecycle costs for a competitor aircraft—in other words, the breakeven is the point at which cost reductions from SUSAN are balanced out by cost increases, making the operation of a SUSAN aircraft equivalent to competitors from an overall cost perspective.

1. Methodology

The SUSAN aircraft is compared against the B737-9MAX for seat class 7 and the B737-8MAX for seat class 6 across capital costs, maintenance costs, and fuel costs. The data and assumptions are described in Table 5.

Table 5 Breakeven Analysis Assumptions

Data Type	B737-9MAX (Seat Class 7)	B737-8MAX (Seat Class 6)	SUSAN
Total Deliveries	Fleet forecasting	Fleet forecasting	Fleet forecasting
Total Block Hours	Fleet forecasting	Fleet forecasting	Fleet forecasting
Average Block Hours per Plane	Assumed 4,000, based on average fleet forecasting	Assumed 4,000, based on average fleet forecasting	Assumed 4,000, based on average fleet forecasting
Fuel Burn (kg)	Fleet forecasting	Fleet forecasting	Fleet forecasting
Total Cost of Fuel Burn	Fuel Burn converted to gallons and combined with price estimate of $2.16/gallon	Fuel Burn converted to gallons and combined with price estimate of $2.16/gallon	Fuel Burn converted to gallons and combined with price estimate of $2.16/gallon
Cost of Fuel Burn per BHR	Total Cost of Fuel Burn divided by Total Block Hours	Total Cost of Fuel Burn divided by Total Block Hours	Total Cost of Fuel Burn divided by Total Block Hours
Maintenance Cost per BHR	$574.40 – sourced from FAA BCA guidance, reduced by 20% [11]	$574.40 – sourced from FAA BCA guidance, reduced by 20% [11]	*Varies based on breakeven test*
Purchase Price	One-half of list price $63.3 million in 2018$ [12]	One-half of list price $59.7 million in 2018$ [12]	*Varies based on breakeven test*
Finance Rate	7.2% [19]	7.2% [19]	7.2% [19]
Depreciation Rate	3.4% [20 – 24]	3.4% [20 – 24]	3.4% [20 – 24]

To conduct a breakeven analysis, costs were compared on a per-plane level across 25 years of analysis. The costs of interest were upfront capital costs, maintenance costs, and fuel costs. All other costs were assumed to be consistent between the comparison aircraft and SUSAN, and were therefore not included in the calculations. The capital costs are calculated as finance and depreciation costs, which are each based on an assumed purchase price of the aircraft and are summed together to estimate the total capital cost. The capital costs account for the age of the aircraft, and accordingly vary by year through the 25-year analysis period. The equation for the finance costs is as follows:

$$Finance = aircraft.price \times e^{(-depreciation.rate \times age)} \times finance.rate \tag{3}$$

The equation for the depreciation costs is as follows:

$$Depreciation = aircraft.price \times [e^{(-depreciation.rate \times age)} - e^{(-depreciation.rate \times (age+1))}] \tag{4}$$

The maintenance costs multiply the assumed number of block hours per plane (4,000, as previously noted) by the average maintenance cost per block hour. This calculation is the same for fuel costs, except the cost used is the average fuel cost per block hour. Block hours, maintenance costs, and fuel costs are not assumed to vary by year—that is, an airplane's utilization and associated maintenance and fuel costs are consistent in real terms for all 25 years of analysis.

All costs are then discounted at a rate of 7%, using Year 1 as the base year, to appropriately capture the net present value of money (i.e., the notion that a dollar today is worth more than a dollar tomorrow).

For the SUSAN aircraft, the list price and maintenance cost per block hour are both set based on the equivalent competitor costs, and vary according to the breakeven test. For instance, the list price could be set fixed at a 40% increase, and the breakeven can then test a variety of maintenance cost increases to see how the results vary accordingly.

To determine when the SUSAN aircraft is cost-effective relative to competitors, the costs from the competitor aircraft are subtracted from the SUSAN aircraft costs, and are then summed over the entire 25-year analysis period. If the total difference is negative, this means that the SUSAN aircraft is cost-effective, as the savings from the fuel costs outweigh the increases in maintenance costs and the purchase price. If the total difference is positive, then the SUSAN aircraft is more costly, as the increases in maintenance costs and the purchase price outweigh the reduction in fuel costs. If it is 0, then that would be considered to be the "breakeven" point at which the cost increases are perfectly balanced by the cost reductions.

2. Results

The results are presented separately for SUSAN aircraft in seat class 7 and seat class 6, although the overall trends are similar. Specific results for a series of values are shown in Table 6. The results indicate points at which the costs of the SUSAN aircraft are perfectly comparable to the competitor aircraft—the savings in fuel costs are balanced out by the assumed increases in purchase price and maintenance costs. To aid in clarity of understanding, a single row in the table is described below as an example of how to interpret the data:

- A 30% reduction in fuel burn that is accompanied by a 30% increase in purchase price can have at most a 15% increase in maintenance cost for SUSAN to remain cost-effective in competition bin 7. For the same fuel burn reduction and percentage increase in purchase price in competition bin 6, maintenance costs can only increase by 11%.

The breakeven data points included in the table represent only a small sample of the possible breakeven points but are broken out for clarity to provide examples of the possible instances in which SUSAN will be cost-effective.

Table 6 Breakeven Analysis Results

Fuel Burn Reduction	***Seat Class 7***		***Seat Class 6***	
	Purchase Price Increase	**Maintenance Cost Increase**	**Purchase Price Increase**	**Maintenance Cost Increase**
30% Reduction	20%	36%	20%	32%
30% Reduction	30%	15%	30%	11%
40% Reduction	20%	63%	20%	56%
40% Reduction	40%	20%	40%	15%
50% Reduction	20%	90%	20%	80%
50% Reduction	50%	25%	50%	19%

The breakeven results can also be expressed graphically as a breakeven line—the area below the line is where SUSAN is cost-effective relative to a competitor, and the area above the line is where SUSAN has overall greater costs than its competitor. Figure 11 shows the breakeven lines for SUSAN in seat class 7 for the three fuel reduction scenarios, and provides an example graphic explaining how to interpret the data in the graph. The following graph, Figure 12, presents the full data for both seat classes.

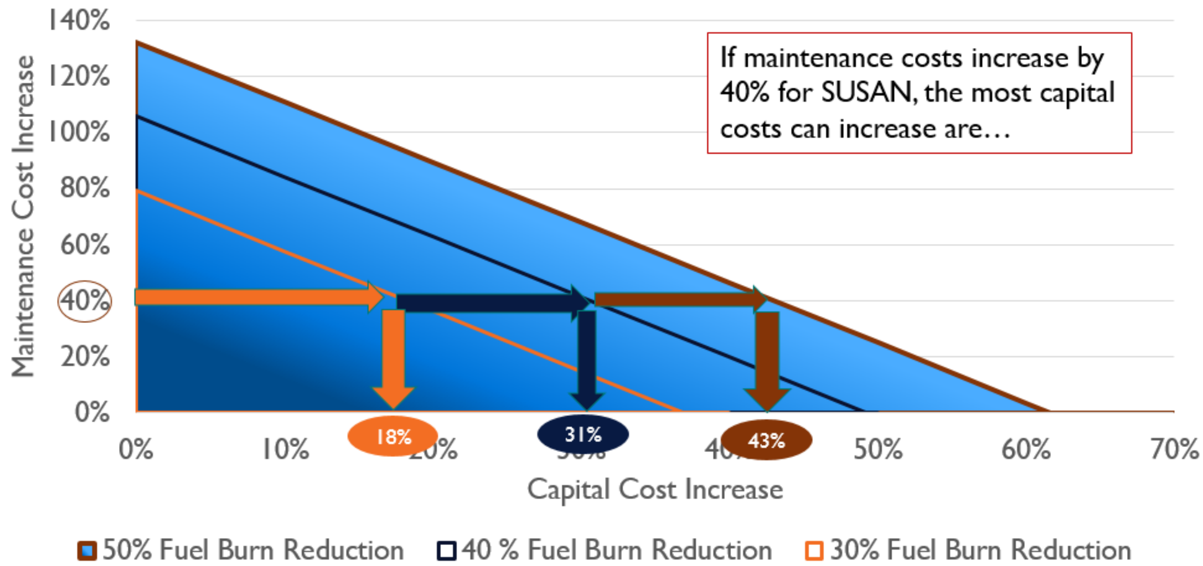

Fig. 11 Breakeven Analysis for Seat Class 7 With Example Graphic

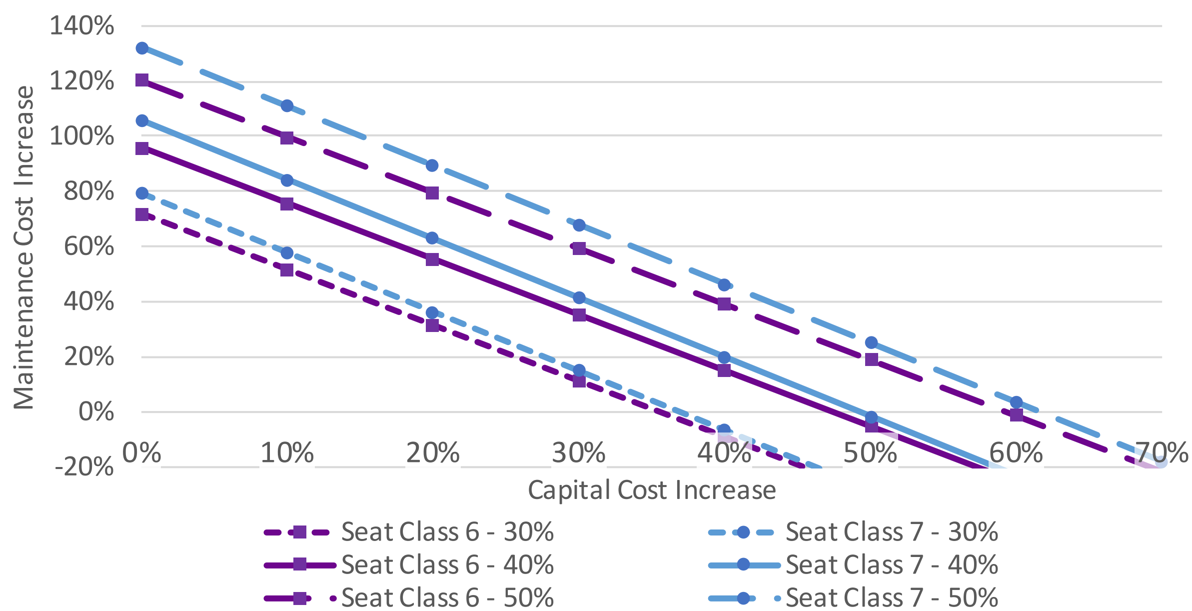

Fig. 12 Breakeven Analysis for Both Seat Classes

Overall, the results from the breakeven analysis suggest that there is a significant potential for SUSAN to be cost-effective relative to competitors. In particular, the maintenance cost per block hour has the potential to double in certain scenarios and still have SUSAN be cost-effective on a per-plane level relative to a competitor. The purchase price is more limited in the amount it can grow, but it seems very plausible that SUSAN could be an effective strategy to reduce costs for an airline. When compared against recent historical analogues with the introduction of the Airbus neo and Boeing MAX family of aircraft, the breakeven analysis is very consistent with expected reductions in fuel burn and increases in capital expenditures. In both cases, these updated family of aircraft saw fuel burn reductions of around 20 percent per passenger mile and list price increases of roughly the same magnitude. The results from the breakeven analysis supports a similar outcome for the SUSAN concept, which is expected to be economically viable under a number of fuel burn reduction scenarios.

IV. Conclusion

Major advancements in aviation history coincide with significant engineering changes such as the reduction of jet engines required for safe and efficient operations. The SUSAN narrow body regional jet concept aims to continue this progress by reducing the need for only a single aft engine, which is poised to reduce fuel burn by up to 40% relative to current aircraft. This paper extended the trade space analysis of the SUSAN concept by first detailing the potential future market for large narrow body aircraft in the U.S. The fleet forecast predicted from the MNL model suggests significant gains for the two largest narrow body size categories the SUSAN aircraft is expected to compete in, making up over 86% of total passenger enplanements by 2050. Second, this analysis provided insight into the future composition of the fleet through a detailed fleet evolution model to compare differing fleet mixes with and without the SUSAN aircraft. These fleet evolution results informed the total operating cost analysis that compared different scenarios of introduction rates for the SUSAN aircraft against the baseline case without SUSAN, demonstrating significant reduction in fuel related costs, and slightly higher total operating costs given the higher capital cost assumptions of the SUSAN aircraft. Finally, these results further informed a breakeven analysis comparing the operational life cycle cost of a SUSAN aircraft against a competitor, with outsized potential for the SUSAN concept to be cost-effective and competitive, even under large increases to capital and maintenance cost factors.

Appendix

Table A1 Summary Statistics of T-100 Data at the Origin-Destination Pair and Aircraft Size Category Level from 2003-2019

	Observations	Mean	Std. Dev.	Min	Max
Aircraft Size Category	317,990	3.40	1.74	1.00	7.00
Revenue Passenger Miles (in millions)	317,990	32.08	121.25	0.00	5,109.28
OD Distance	317,990	705.59	592.37	2.00	4,983.00
Operations (Departures)	317,990	468.79	1210.78	1.00	31,267.00
Passengers	317,990	36,665.44	108540.10	1.00	2,453,222.00
Market Size (# of available categories)	317,990	2.57	1.67	1.00	7.00
Origin Hub	317,990	0.34	0.47	0.00	1.00
Destination Hub	317,990	0.28	0.45	0.00	1.00
OD Hub	317,990	0.10	0.30	0.00	1.00
Segment Length	317,990	2.50	1.13	1.00	5.00

Table A2 Multinomial Logit Model Results for Aircraft Category Choice (2003-2019)

Aircraft Size Category	Constant	Revenue Passenger Miles (RPMs in millions)	Market Size (# of available categories)	Origin Hub	Destinati on Hub	Both OD Hubs	Segment Length 250-500 miles	Segment Length 501-1200 miles	Segment Length 1201-2000 miles	Segment Length 2001+ miles	Linear Trend
Category 1: Piston/Turbo Prop ≤ 100 Seats	Base Outcome	-	-	-	-	-	-	-	-	-	-
Category 2: Regional Jets 25-100 Seats	-2.23*** (.02)	.013*** (6.4e-04)	.467*** (8.4e-03)	-.393*** (.065)	.348*** (.023)	.798*** (.067)	1.48*** (.016)	3.47*** (.025)	4.83*** (.139)	4.19*** (.508)	.048*** (1.4e-03)
Category 3: Narrow Bodies 101-125 Seats	-3.99*** (.029)	.011*** (6.5e-04)	.925*** (9.2e-03)	-.406*** (.067)	.313*** (.028)	.733*** (.07)	1.73*** (.024)	4.15*** (.029)	6.92*** (.14)	8.39*** (.501)	-.048*** (1.7e-03)
Category 4: Narrow Bodies 126-150 Seats	-3.35*** (.023)	.015*** (6.4e-04)	.712*** (8.7e-03)	-.814*** (.067)	.24*** (.025)	1.11*** (.069)	1.66*** (.019)	4.12*** (.026)	7*** (.139)	8.05*** (.501)	.027*** (1.5e-03)
Category 5: Narrow Bodies 151-175 Seats	-4.68*** (.027)	.013*** (6.4e-04)	.806*** (9.0e-03)	-.599*** (.067)	.22*** (.026)	.788*** (.07)	1.79*** (.022)	4.33*** (.028)	7.37*** (.139)	8.99*** (.501)	.09*** (1.6e-03)
Category 6: Narrow Bodies 176+ Seats	-5.66*** (.03)	.014*** (6.4e-04)	.919*** (9.4e-03)	-.574*** (.067)	.481*** (.028)	1.11*** (.071)	1.73*** (.026)	4.28*** (.03)	7.48*** (.14)	9.27*** (.501)	.092*** (1.8e-03)
Category 7: Wide Bodies	-7.61*** (.054)	.012*** (6.6e-04)	1.23*** (.012)	-.265*** (.071)	.669*** (.043)	.903*** (.079)	1.64*** (.043)	4.37*** (.043)	7.95*** (.144)	10.5*** (.502)	.012*** (2.5e-03)
Observations:	317,990										

Wald Chi^2	94808.53	**Notes:** coefficients reported as relative-risk ratios (transformed by exp^{β}). Standard errors are reported in parenthesis: * p<0.05 ** p<0.01 *** p<0.001
Pseudo R^2	0.1658	

Table A3 Fleet Assumptions for In-Service Fleet Calculation (BTS T-100 and Form 41 P5.2)

Aircraft Seat Class	Annual Utilization (Block Hours)	Average Speed (MPH)	Average Capacity (Seats)
RJ 25-100 Seats	2,643	384	64
NB 101-125 Seats	2,874	421	114
NB 126-150 Seats	2,662	430	142
NB 151-175 Seats	3,620	453	164
NB 176+ Seats	3,838	459	187
WB	3,521	494	267

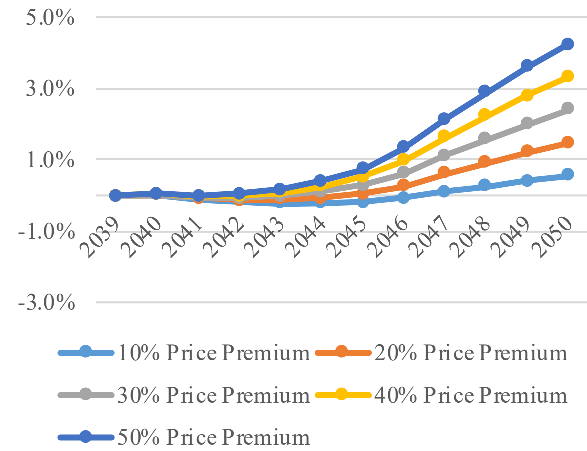

Fig. A1 Total Costs – TT, 30% Fuel Reduction

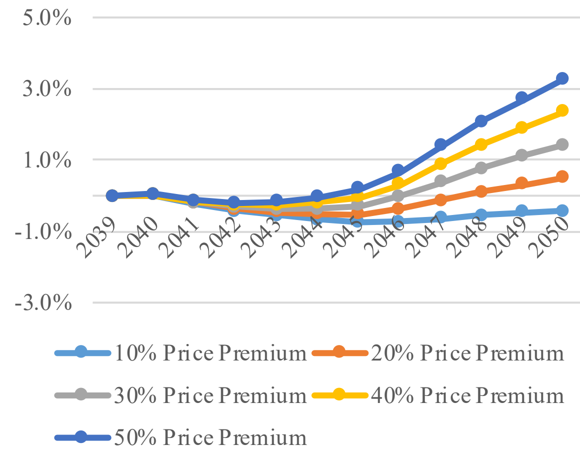

Fig. A2 Total Costs – TT, 40% Fuel Reduction

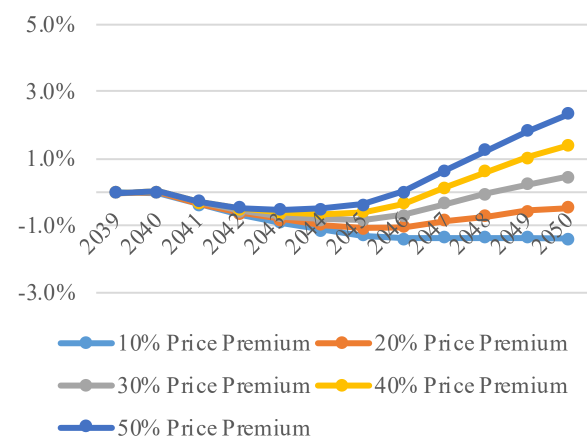

Fig. A3 Total Costs – TT, 50% Fuel Reduction

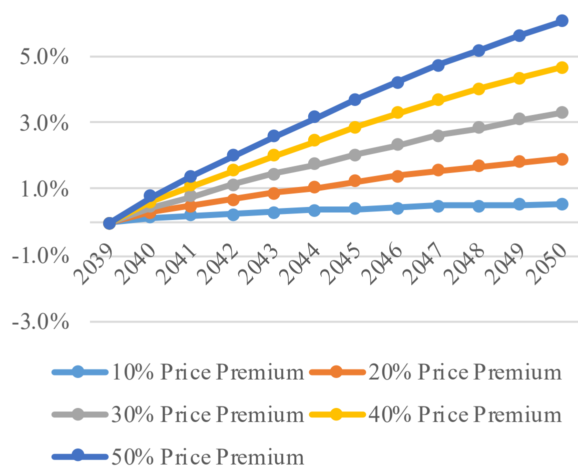

Fig. A4 Total Costs – ALL, 30% Fuel Reduction

Fig. A5 Total Costs – ALL, 40% Fuel Reduction

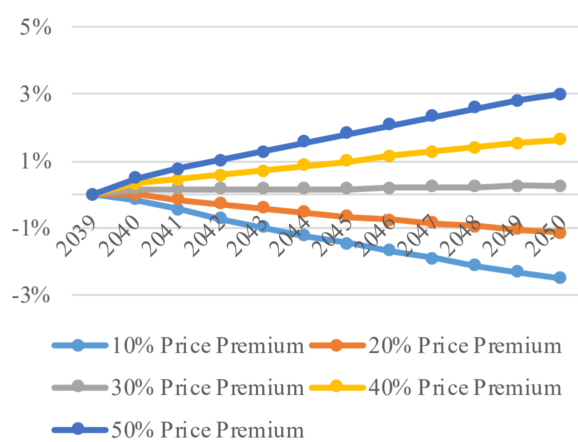

Fig. A6 Total Costs – ALL, 50% Fuel Reduction

Acknowledgments

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